

***NEUTRON EMISSION EXPERIMENT ON THE MEGAJOULE
PLASMA-FOCUS FACILITY OPERATED AT THE IPPLM.***

REPORT

I. Introduction

Dense Plasma Focus (DPF) machines are pulsed discharges in which microinstabilities and turbulence lead to the generation of powerful beams of electrons, ions, large emission of X-rays and of fusion neutrons and protons when the fill gas is deuterium. The Plasma-Focus (PF) belongs to the family of the dynamic Z-pinch. It is a two-dimensional Z-pinch formed on the axis at the end of a coaxial electrode system of a plasma accelerator. Most realizations belongs to one of the two following geometrical types:

- Mather type is characterized by a small anode aspect ratio (diameter/length < 1);
- Filippov type is characterized by a large aspect ratio.

Plasma-Focus produces a short living, rather dense plasma, which properties are dominated by the occurrence of macroscopic and microscopic instabilities. At present DPF is one of the most intense of neutron emission. Also scaling laws of neutron yield prepared on a basis of a long experience with different devices of the type are very promising. Unfortunately, it was found that neutron emission saturates for energy level of several hundreds kJ.

The main goals of experiments performed within the frame of the Contract are:

1. Achievement of a maximum neutron yield for stored energy 200-800 kJ. Determination of the energy for which neutron yield saturates (if any).
2. Determination of neutron emission characteristics (time distribution, emission anisotropy, relative contribution of different mechanisms to Y_{tot} etc.) ;
3. Investigation of the relation between the neutron yield and plasma sheath dynamics and plasma sheath structure, particular attention should be paid to the pinch filamentation phenomenon and its connection with the neutron yield.

The report is supplemented with Appendices (financial, scientific and technical).

II. Review of PF experiments carried out at the IPPLM

Experiments with PF facilities were started at the Institute of Plasma Physics and Laser Microfusion about thirty years ago. The first PF facilities i.e. PF-20 and PF-150 machines (the numbers denote maximal electrical energies stored in the condenser bank) were built at the IPP&LM almost thirty years ago.

The investigations carried out concentrated mainly on the following problems:

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14. ABSTRACT

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1. optimization of the PF facilities in order to achieve the highest possible neutron yield [1,2],
2. definition of the neutron production mechanisms [3,4],
3. investigations of the correlation between neutron yield and:
 - current sheath dynamics
 - current sheath structure
 - pinch disintegration process [5,6,7].

These investigations were continued in the 80-tieth on the PF-360 facility [7,8]. The PF-360 facility was constructed as a „pilotage” machine for the big PF-1000 device. Also some components designed and manufactured previously for the PF-1000 machine were utilized for the PF-360 construction. Therefore, the PF-360 facility was, to some degree similar to the PF-1000 one. The data collected on the PF-360 machine were essential and made possible to optimize roughly the PF-1000 final construction.

Table 1 contains the most important operational parameters of the PF-150, PF-360 and PF-1000 facilities. Table 2 contains characteristic data related to the current sheath and plasma column. These data were obtained by means of „optical” diagnostics (interferometer, schlierenography etc.) The following conclusions can be drawn from these data:

1. Maximum radial velocities of the current sheath are almost the same in the both facilities. One can suppose then that at the moment when (and right before) the MHD instabilities start to grow the thermal conditions inside the pinch plasma are almost the same. One cannot expect that neutron production by thermal interactions can differ essentially in the both facilities.
2. In large PF facilities thickness and curvature radius of the current sheath nearby the electrode end are significantly larger than in small ones. Due to that, plasma density gradient (along the pinch axis) is small and outflow of the plasma along the pinch axis is decreased. In consequence, the pinch is more stable.

Intensive axial outflow in the PF-150 machine resulted usually in rapid ruptures of the plasma column. Whereas in the PF-360 machine the radial expansion phase proceed the start to grow $m=0$ MHD instabilities. Due to relatively long duration of the expansion a state of equilibrium of the pressure in whole volume of the plasma column was established. Therefore, the instabilities could develop simultaneously along the whole length of the plasma column [7]. Significantly longer lifetime of the pinch in the larger PF facility was an effect of quite different character of the disintegration processes.

The observations mentioned above are very important from the point of view of the neutron production mechanisms. Choosing suitable discharge parameters (pressure, voltage etc.) one can regulate which kind of nuclear reaction initiation is predominant; thermonuclear or acceleration (reactions initiated by accelerated ions). Experimental studies performed on the PF-150 facility and refereed to the relation between pinch lifetime and neutron yield showed that: $Y_n \sim 1/\tau_i$ [9]. Because τ_i increases considerable in large PF facilities one can expect that the contribution of the acceleration mechanism of neutron production can decrease in that kind of devices.

The contributions of other, equally efficacious neutron production mechanism should be increased in order to fulfill the scaling laws: $Y_n \sim W_o^{2+2.4}$, $Y_n \sim I_{\max}^{3.2+3.3}$ (where W_o - condenser bank energy, I_{\max} - maximum discharge current).

Experimental studies carried out on PF facilities of different discharge energy supplied very interesting data on neutron production mechanism. In relatively small PF machines (i.e.

PF-20, PF-150) neutron emission does not appear till the pinch MHD $m = 0$ instability starts to grow. Simultaneously an angular distribution with a considerably coefficient of anisotropy was measured: $A > 1$ ($A = Y_n^{\text{end-on}} / Y_n^{\text{side-on}}$). In large PF-facilities (PF-360, Poseidon) there were observed two neutron emission pulses. First one was coincided with the moment of maximum pinch compression [10] and after this main neutron emission pulse connected with the moment of pinch disintegration was observed. That earlier emission was characterized by $A < 1$ which proves that these neutrons were mostly produced by deuterons with significant azimuthal motions.

The neutron emission at the moment of maximum pinch compression (in this earlier pulse) is almost $2 \div 3$ order of magnitude higher than the theoretical emission estimated on the base of thermal parameters of the plasma H.J.Kaeppler et.al. [11] suggested than, that the MHD instabilities of the $m=2$ and $m=4$ types, which grow during the collapse phase are the main reason of the neutron production. They cause that the pinch region is composed of a central filament and spiral outer ones. Such pinch structure leads to complex axially - radial motions of deuterons. These deuterons can imitate significant number of D-D reactions. Pictures taken with a pinhole camera reveled this filamentary structure of the pinch region [10]. We expect that this pinch structure could be additionally confirmed by pictures taken with a frame X-ray camera. It was estimated that neutron produced in this earlier pulse amounted even to 80-85% of the total neutron yield, especially in the discharges performed on the Poseidon facility when a ceramic insulator was used.

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III. Plasma-Focus PF-1000

The neutron experiments have been performed on 1.2 MJ Plasma-Focus PF-1000 facility operating at the IPPLM. The PF-1000 consist of three main elements:

- the condenser bank and pulsed electrical power circuit driving the plasma discharge,
- the mechanical, vacuum and gas system consisting of the vacuum chamber, coaxial electrode, vacuum and gas handling system,
- the data acquisition and diagnostics system.

Figure 1 is a schematic diagram of the coaxial plasma-focus apparatus. The design shown in Fig. 1 consists of two coaxial electrodes and a alumina insulator across which the initial breakdown occurs. The outer electrode (OE) consists of the 24 stainless steel rods. The rod diameter is 32 mm. The outer electrode (OE) and copper center electrode (CE) diameters are 400 and 231 mm, respectively, with CE length of 600 mm. The minimum annular spacing is $\Delta r = 68.5$ mm. The OE is attached to a circular grounded cable header (Fig.2). The CE attaches to a central header that provides an electrical connection and vacuum seal. The cylindrical alumina insulator sits on the CE (Fig.1). The main part of the insulator extends 113 mm along the CE into the vacuum chamber. This insulator prescribes the shape of the initial current sheath between the CE and the back plate of the OE. The vacuum vessel of stainless steel surrounds the electrode structure (Fig.3). The vacuum chamber has large dimensions (1400 mm in diameter and 2500 mm in length). Ordinary vacuum technology, utilizing oil-diffusion pumps and antireep liquid N_2 traps is employed. This system permits to reach pressure in the chamber of the order of $6 \cdot 10^{-5}$ mbar.

The condenser bank (1200 kJ) system consists of twelve condenser modules each comprising twenty four 50 kV, 4.625 μ F low inductance condensers connected in parallel (Fig.4).

The electric energy is transferred to a collector and electrodes by means low-inductance cables. The importance of low-inductance cables, condensers, and switches in power supply cannot be overstressed if the large tube currents are to be achieved.

Summarizing, parameters of the PF-1000 generator areas follows:

- the charging voltage - $U_0 = 20\ 4\ 45$ kV,
- the condenser bank capacitance - $C_0 = 1.332$ mF,
- the initial capacitor bank energy - $E_0 = 266\ 4\ 1064$ kJ,
- the min. inductance - $L_0 = 8.9$ nH,
- the quarter discharge time - $t_{1/4} = 5.4$ μ s,
- the short-circuit current - $I_{SC} = 15$ MA,
- the characteristic impedance - $Z_0 = 2.6$ m Ω ,

IV. Diagnostic systems

Current and voltage measurements.

The basic diagnostics performed in the study of any plasma focus device are measurements of the discharge current and the voltage drop across its electrodes. The discharge current of the plasma focus is measured using a Rogowski coil (total current) or magnetic probe (localized current distribution). The current and the time derivative of the current of typically plasma focus discharge registered on PF-1000 device are shown in Fig.5. The sharp derivative spike and current dip are features typical of focusing discharge in which a large increase of the plasma sheath impedance occurs.

X-ray emission measurements

The plasma produced at the pinch phase of the plasma focus is an intense source of radiation, including X-rays. Hence, it is essential to incorporate X-ray detection system in to the PF device.

The time evolution of the X-ray emission from the plasma focus was obtained using a soft X-ray PIN diodes placed outside the chamber. This type of X-ray detector can be used for wavelengths from 0.1 to 1 nm. Typical PIN diodes signals are presented on Fig.5.

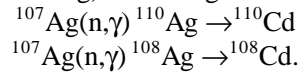
The hard X-ray radiation (shorter than 0.1 nm) was measured outside of main discharge chamber by means scintillation counter, consisted of a scintillation detector (of 30 cm in diameter and 30 cm of length) and a fast photomultiplier of the XP-2040 type. It was located at a distance of 4.8 m. from the electrode outlet.

To monitor the soft X-ray emission we used a pinhole camera. The camera was equipped with two pinholes, which were covered with Be-filters of 10 μm . and 25 μm . in thickness, respectively. Time-integrated pinhole pictures were registered with X-ray films of the RAR type.

Space resolved spectral measurement were performed with an X-ray spectrograph equipped with a mica crystal bent spherically. The crystal with $2d=19.94 \text{ \AA}$ had a curvature radius equal 186 mm. The spectrograph was arranged side-on the PF-1000 facility, at a distance of 100 cm from the inner electrode axis (Fig 6).

Neutron emission measurements

The neutron counting equipment is based on silver activation technique. A hollow cylinder of polythene moderates the fast neutrons. The thermalized neutrons activate a natural silver foil (51.8% of ^{107}Ag and 48.2% of ^{109}Ag) according to the reactions



with cross section of 113 ± 13 barn and 45 ± 4 barn respectively. A thick silver foil is wrapped around an LMT Geiger tube. Position of our counters with respect to the plasma-focus is presented on Fig. 7.

The calibration of the counting equipment is difficult due to:

- the high neutron yield of the plasma focus and the large dynamics of the measurement (from 10^9 to 10^{12} neutrons per shot),
- the proximity of the neutron counter to the focus and the effect of fast neutron scattering require in-situ calibrations.

A neutron yield Y (neutron/shot) of the plasma focus is related to the number of beta counts N_{12} measured between, say, $t_1 = 1$ and $t_2 = 50$ s after the shot of the plasma focus machine has occurred, by the relationship $Y = W_{cal} N_{12}$ in which W_{cal} (neutron/shot count) is a calibration constant of the counter when operated between t_1 and t_2 . In our experiment we determined W_{cal} by using a radioactive neutron source and method based on the measurement of the count rate after source removal.

A Am-Be neutron source having a neutron spectrum well centered around 2.5 MeV, of strength $I_0 = 1.5 \cdot 10^7$ neutrons/s was located on the end of the anode of the plasma focus device practically in the same position where a plasma column forms. To ensure reproducibility of the positioning, the source was supported by a purposely designed source holder which did not perturb a neutron emission. The radioactive neutron source is left in position until saturation is reached. After reaching saturation level, the source was swiftly removed from the experiment site (at a time t_r). Removal time (being of the order of 1s) was short in comparison with the smallest of the half-life time (24.6 s) characterizing the decay of the silver radioisotopes. Following the removal, beta counts are taken from t_r to $t_s = t_r + t_{CR}$ and $t_2 = t_s + T_2$.

Exemplary numbers of counts N_{12} after plasma focus discharge (shot n° 8/12/01/00) for all the counters and calculated neutron yields are presented below:

Number of the counter (Fig.7)	Counts N_{12}	Neutron Yield
C 1	6031-39	$(5.57 \pm 0.10) \cdot 10^9$
C 2	9820-60	$(4.65 \pm 0.65) \cdot 10^9$
C 3	4877-33	$(5.04 \pm 0.82) \cdot 10^9$
C 5	2195-49	$(5.20 \pm 0.16) \cdot 10^9$

Time dependence of the neutron emission was registered using two Transient Pulses Capturing Systems (scintillator with photomultipliers) placed in a mobile EMC seal eurorak HF cabinets (Fig.8).

Optical diagnostics

Information about the dynamics of the plasma focus discharge can be obtained by means of electro-optical image converter streak camera (time resolution 0.1-10ns, spectral range 300-900 nm, amplification factor 10^6) placed side-on and has been provided with optical filters UG-5 fitted to register Cu I line ($\lambda = 510$ nm). In the case of a “good” shot the implosion is very fast and the pinch is narrow (Fig. 9a). In this case two consecutive pinching events have been observed. In the “bad” shot the implosion was slow and pinch radius was larger and diffused (Fig. 9b). These photos we obtained in the experiment with the following PF-1000 parameters: capacity of condenser bank $C_0 = 1.332$ mF, initial charging voltage $U_0 = 30$ kV (initial capacitor bank energy was about $E_0 = 600$ kJ), the

maximum discharge current $I_0 = 1.5$ MA and the current rise time was equal $t_0 = 8$ μ s. The discharge chamber was filled with deuterium under initial pressure $p_0 = 3.9$ mbar.

Data acquisition and synchronization system

A mobile stand for multi-channel acquisition system has been prepared to register electrical signals from diagnostic subsystems (Fig.10). The system is placed in a twin EMC seal eurorak HF cabinet and it is equipped with 20 ST connectors and fiber optics patch-cords allowing to transmit optical signals to all diagnostic subsystems.

The scheme of diagnostic arrangements used during experiments are presented on Fig.11.

V. Description of activity

Within the frame of the Contract the following steps have been performed:

- Designing and assembling of elements of the diagnostic system necessary for achievements of the Contract goals (neutron counters, neutron probes, data acquisition system);
- Testing of the electrical and vacuum system of the PF-1000 facility operating on the energy levels above 0.5 MJ;
- Testing of the diagnostic equipment for measuring current (Rogowski coil and magnetic probe), plasma sheath dynamic (streak camera), X-ray signals (PIN diode and filter scintillator – PMT), neutron signals (filter scintillator PMT) and neutron yield (silver activation counters);
- Testing of the acquisition system of electrical signals from different diagnostic instruments and the system of synchronization of the whole experiment;
- Calibration of neutron silver counters by use a radioactive neutron source;
- Training of the PF insulator surface to the moment of a start a neutron yield on 10^0 [neutrons/shot] level.
- Measurements of the neutron yield and its dependence on the external parameters (applied voltage, capacitance, filling gas pressure),
- Determination of neutron emission characteristics (time distribution, emission anisotropy),
- Investigation of correlation between neutron yield and dynamics of the plasma sheath.

APPENDIX I.

Financial report*

Within the frame of the Contract we have bought the following elements of the mobile stand for multi-channel waveforms acquisition:

• Digital Phosphor Oscilloscope TDS 3052	2x	-	16.274	US\$
• Basic electronic elements		-	6.013	US\$
• Special connectors to assemblies SUCOFLEX		-	3.535	US\$
• Labor		-	4.720	US\$
• GPIB/AT S3FG220 card		-	634	US\$
• Minicomputer PC with monitor		-	872	US\$
• Deuterium		-	779	US\$

Total	-----	32.827	US\$
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* The financial report is preliminary as the last check (10.000 US\$) materialized as a cash on 25th of July.

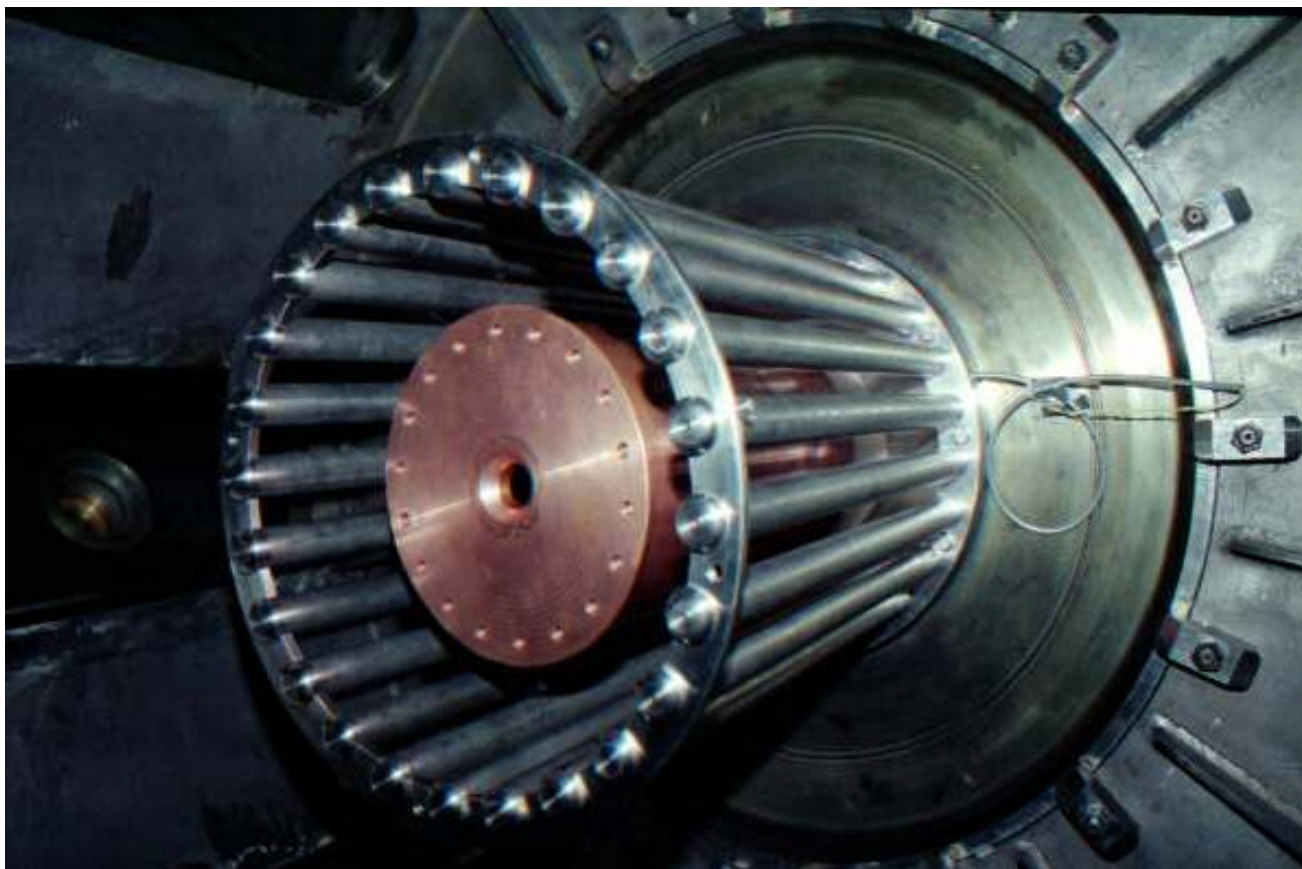


Figure 2. The outer and central electrodes.

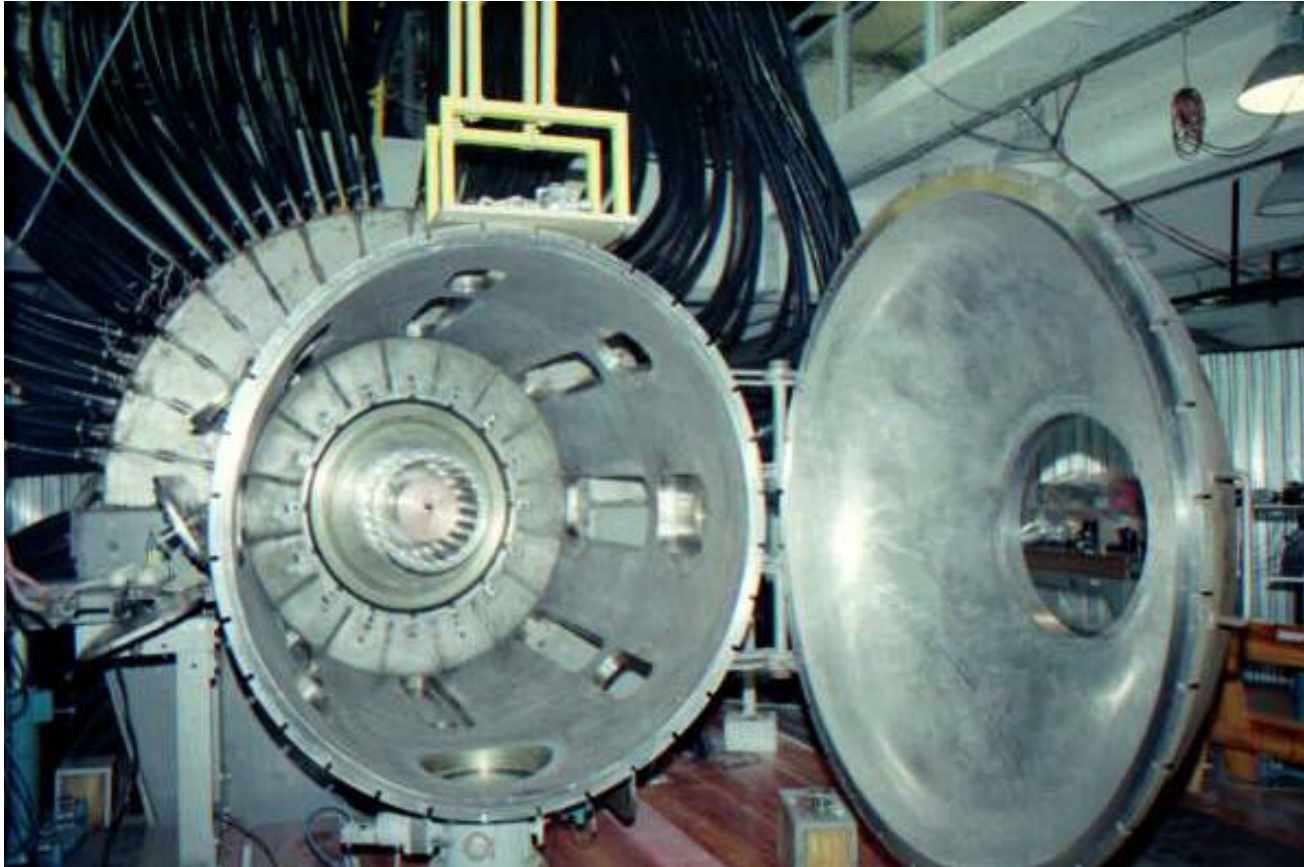
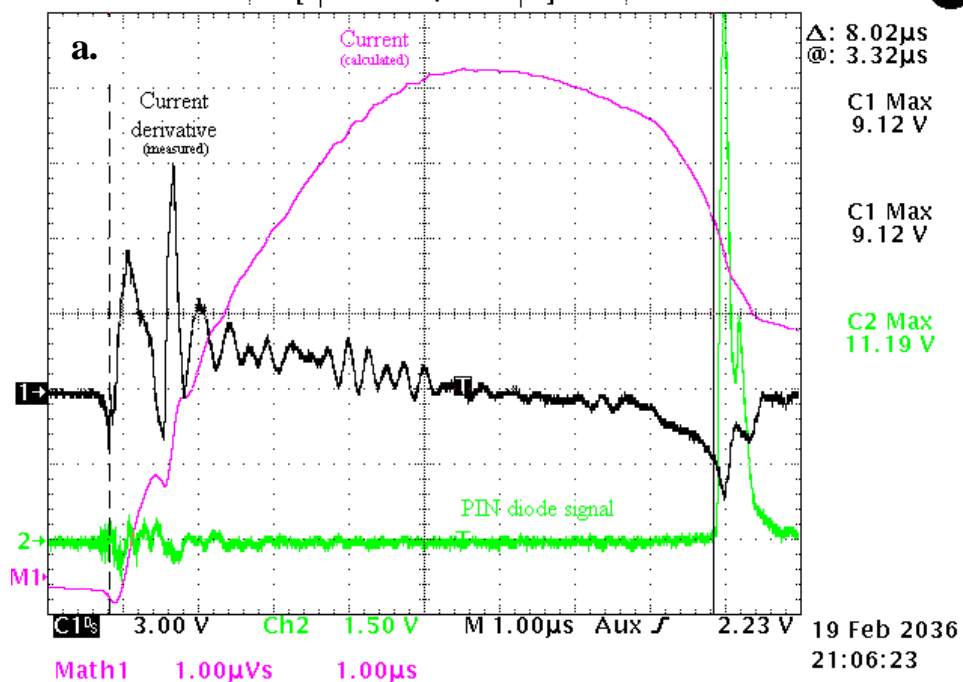


Figure 3. The PF-1000 plasma-focus chamber.



Figure 4. The condenser battery module.

Tek Stop: Single Seq 1.00GS/s



Tek Stop: Single Seq 1.00GS/s

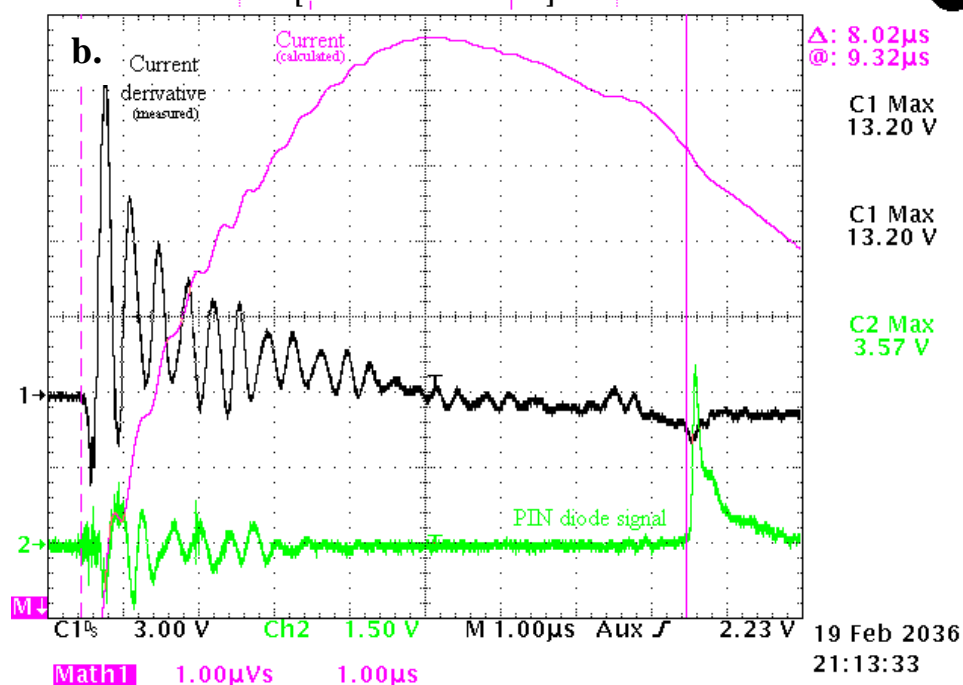


Figure 5. Typical waveforms current time derivative, PIN diode signal, and current of the PF-1000 discharge (a. shot n° 8/12/01/00, b. shot n° 6/12/01/00). A general experimental data: charging voltage - 30 kV, stored energy - 600 kJ, filling gas pressure - $D_2/3.9$ mbar.